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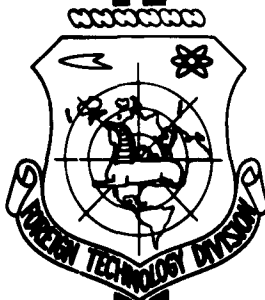
TRANSLATION

PROBLEM OF EMPLOYING ELECTRONIC FEELERS TO MEASURE
VIBRATION AMPLITUDES AND FREQUENCIES

By

Yu. D. Korniyushkin

FOREIGN TECHNOLOGY DIVISION



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FIRST LINE OF TEXT

Problem of Employing Electronic Feelers to Measure Vibration Amplitudes and Frequencies

by

Yu. D. Korniyushkin

In this report are described developed and tested electronic tubes with mechanically controlled electrodes, intended for measuring vibration amplitudes and frequencies.

To reliably measure amplitudes and frequencies of vibrations such feelers should possess satisfactory mechanical and electrical qualities. That means that feelers should possess sufficient vibrational strength and have a sufficiently monotonous frequency characteristic, i.e. have a minimum number of overtones in the working range of frequencies. Feelers should also have a linear characteristic of the dependence of the output signal upon the displacement of the feeler in working range of measurements.

Experience shows, that satisfactory frequency characteristics can be obtained only at maximum structural simplicity of the input electrodes. Any complication may lead to the appearance of additional overtones and narrowing the length of the working section of the frequency spectrum. Consequently, the selected type of sensitive system from the mechanical viewpoint should be most simple. These requirements are fulfilled to a large extent by a sensitive system - twin end diode [1], which at maximum simplicity still has sufficient sensitivity.

Sensitive system of feeler

The twin end diode chosen in the role of sensitive system, in conformity with the ideas explained above, represents a system of electrodes, consisting of an oxide coated cathode with grid and two anodes (fig.1).

The movable electrodes can be either cathode with grid, or the anodes. Displacement is in transverse direction (arrow in fig.1.), and depending upon the magnitude of relative displacement there is a change in plate current, which flows through each one of the anodes.

Experience shows, that in a definite interval of displacements, in constructions of such type sensitive systems, is observed a linear dependence between the current in bridge diagonal, into the circuit of which the feeler is connected, and relative bias.

To determine the magnitude of the linear section was especially constructed a tube with the mentioned sensitive system. The tube had a fixed lead out running through an elastic membrane which allowed to fix the necessary displacement for the cathode with the aid of a micrometer. The anodes were secured to rigid cross pieces and were stationary. In the bridge diagonal could be measured the current differential, depending upon the differential. In fig.2 and 3 is shown the construction of the tube and its outer form.

The results of testing the tube are given in form of graphs in fig.4, from which is evident, that the length of the linear section 3.0 mm at a displacement of the mobile electrode in one side. Such greater length of the linear section allows to measure reliably the oscillation amplitudes of considerable magnitude.

The feelers described in the report possess such a sensitivity with respect to current, that they permit direct recording of the signal by means of proper self-recording instruments, e.g. with the MFO-2 type oscillograph without preliminary amplification.

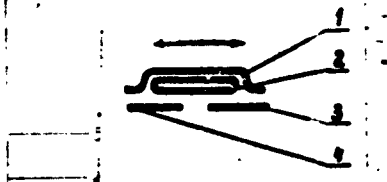


Fig.1. Schematic of sensitive system of twin end diode type.

Structural dimensions of feeler's sensitive system are as follows (in mm): oxide coated cathode 3×11 ; anode $0.1 \times 5 \times 10$; distance between anodes 1.5; distance between anodes and cathode 1.5; screen (grid) $4 \times 2 \times 12$.

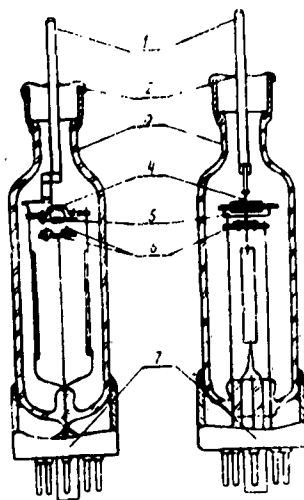


Fig. 2. Electronic tube with movable inlet (1-rigid movable inlet-lead in; 2-elastic membrane; 3-feeler balloon; 4-screen; 5-cathode; 6-anodes; 7-base).

Mechanical system (elastic suspension)

The mechanical system is intended to create relative displacement of electrodes.

The requirements for it are.

1. Displacement of electrodes should be in transverse, with respect to cathode and anodes, direction.

2. Displacement of movable electrode should be proportional to the displacement of feeler body, because the feeler is intended for measuring vibration amplitudes.

These requirements are best fulfilled by a bracket beam, having concentrated mass at the tip, which executes lateral oscillations under the effect of an induced force. In this way, as basis should be used a mechanical system, which represents an elastic system with internal inert mass.

It can be shown [2], that displacement of a centered mass on the end of an elastic rod relative to the block up under the effect of harmonic induced force

$$z = z_0 \cos(pt - \varphi).$$



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Fig. 3. Outer appearance of electronic tube with movable lead-in.

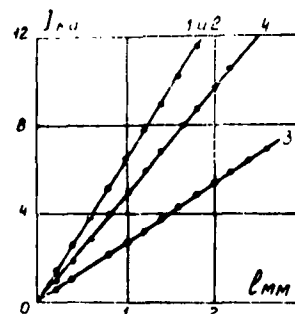


Fig. 4. Dependence of unbalance current upon displacement (bias).

where

$$z = z_0 \cos pt - \tau),$$

$$z_0 = \frac{\left(\frac{p}{\omega_0}\right)^2 y_0}{\sqrt{\left(1 - \frac{p^2}{\omega_0^2}\right)^2 + \frac{p^2}{\omega_0^2} \varepsilon^2}}, \quad (1)$$

$$\lg \tau = \frac{\frac{p}{\omega_0}}{1 - \frac{p^2}{\omega_0^2}} \cdot \pi = \frac{2\theta}{\omega_0},$$

where p - angular frequency of induced force; y_0 - oscillation amplitude of block up;
 ω_0 - natural angular frequency of oscillations; ε - coefficient of attenuating oscillations.

From (1), in particular, is evident, that at $1 \ll \frac{p^2}{\omega_0^2}$ and $\varepsilon^2 \ll \frac{p^2}{\omega_0^2}$ $z_0 = y_0$, oscillation of the inert mass is realized with the very same amplitude (and also frequency), as the oscillation of the block up (sealing). Consequently, during the operation of the amplitude meter it is necessary, that the natural frequency of the mechanical system should be by many times lower than the working frequency of oscillations; the more accurate will be, in this case, the performance of the feeler. We will discuss below this condition, limiting this statement.

The natural frequency of rod oscillations, rod with centered mass at the tip is determined by expression [3]

$$f_0 = \frac{1}{2\pi l} \sqrt{\frac{EJ}{ml}}, \quad (2)$$

where E - elasticity modulus of the material; J - moment of inertia of cross section relative to the axis, passing through the CG perpendicularly in direction of the bend; m - mass of rod; l - length of rod; δ - solution of equation of the type

$$1 + \lambda^2 \operatorname{ch} \delta \cos \delta - \lambda^2 \operatorname{ch} \delta \sin \delta - \cos^2 \delta \sinh^2 \delta = 0, \quad (3)$$

where $\lambda = \frac{M}{m}$, M - magnitude of centered mass.

The solution of equation (3) offers a series of roots. Physically this means, that together with the natural frequency in such a mechanical system, there should unavoidably originate overtones. A graphis solution of equation (3) is given in re-

part [3].

Calculation of Amplitude Measurer

As is evident from (1), for satisfactory operation of the feeler in the role of an amplitude measuring device the following conditions have to be fulfilled

$$\left. \begin{aligned} \frac{p^2}{\omega_0^2} &\gg 1, \\ \frac{p^2}{\omega_0^2} &\gg 1. \end{aligned} \right\} \quad (4)$$

We will assume, that the measurement of amplitudes should be made with an accuracy of $\pm 1\%$. This means that

$$\left| \frac{z_0 - y_0}{y_0} \right| < 0.01 \quad (4a)$$

Substituting the value z_0 from (1), we will obtain

$$\left| \frac{\left(\frac{p}{\omega_0}\right)^2}{\sqrt{\left(1 - \frac{p^2}{\omega_0^2}\right)^2 + \frac{p^2}{\omega_0^2}}} - 1 \right| < 0.01 \quad (4b)$$

In practice the inequality $\frac{p^2}{\omega_0^2} \ll 1$ is normally fulfilled. Consequently the above written expression can be simplified

$$\frac{\frac{p^2}{\omega_0^2}}{\frac{p^2}{\omega_0^2} - 1} - 1 < 0.01 \quad (4c)$$

or after elementary transforms for the specific case, we have

$$\frac{p}{\omega_0} = \frac{f_{\text{res}}}{f_0} = \sqrt{\frac{1}{\sigma} + 1}. \quad (4d)$$

In this way is determined the minimum working frequency

$$f_{\text{res min}} = f_0 \sqrt{\frac{1}{\sigma} + 1}. \quad (5)$$

In fig.5 is given a graph $\frac{f_{\text{work min}}}{f_0} = f(\sigma)$, corresponding to equation (5). From fig.5 is especially evident, that in proportion to the rise in measurement accuracy ($\sigma < 1\%$) the ratio $\frac{f_{\text{work min}}}{f_0}$ rises sharply, i.e.

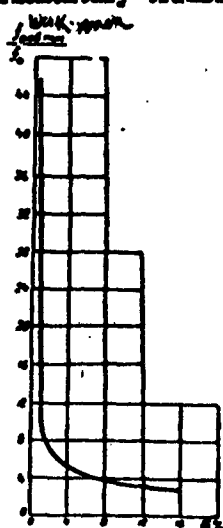


Fig.5. Dependence of minimum working frequency upon measurement accuracy.

the higher measurement accuracy requirement lead to narrowing the effective frequency range.

Structurally it is difficult to make a feeler with satisfactory frequency characteristic, for which $\frac{f_{\text{work}}}{f_0}$ is small, and the measurement accuracy high. Practice shows, that the accuracy of the feeler should be selected at 5% during operation at low frequencies. As the working frequency increases the accuracy will rise sharply and at $\frac{f_{\text{work}}}{f_0} = 10$ the measurement accuracy will reach 1%.

And so, when selecting the relative error of the amplitude meter of 5%, we have $\frac{f_{\text{work min}}}{f_0} \approx 4.3$.

It should be mentioned, that formula (2) compiled in the assumption, which does not always justify itself in practice. Consequently a certain discrepancy between calculated and experimental results is possible. And the fact is, experience shows, that calculation of natural frequency by formula (2) does not always lead to satisfactory conformity with experiment.

The reasons here can be of various nature: surface hardening, local annealing, heterogeneity of the material etc. These qualities of the material are in no way taken into consideration by formula (2).

That is why when constructing a mechanical system it is advisable to follow the semi-empirical method: at first plot a dependence graph between the length of the bracket beam and the frequency of natural oscillations at given inert mass, and then already by formulas:

$$\frac{l_1}{l_2} = \left(\frac{d_1}{d_2}\right)^4 \approx \frac{M_1}{M_2} = \left(\frac{d_1}{d_2}\right)^2 \frac{l_1}{l_2} \quad (6)$$

emanating from formula (2) in relation to the ratio of basic and first resonance frequency, to select optimum structural dimensions.

Here in (6)... l_1, l_2 - linear dimensions of elastic rods; d_1, d_2 - their diameters; M_1, M_2 , centered masses on their tips, for which natural and first resonant frequencies are identical.

On the basis of the concluded investigation were established the optimum structural dimensions of the elastic system (material Mo); $L = 35$ mm; $M = 0.53$ g; $d = 0.5$ mm.

Such a system had a basic frequency $f_0 = 48$ c and frequency of the first overtone $f_{01} = 970$ c.

Description of feeler construction

In the developed construction was used a sensitive system of the twin end diode type. Two bracket beams served as the elastic system, to the ends of which were attached anodes together with additional loads. In this way in the process of operation the anodes execute an oscillatory motion relative to the position of equilibrium. Drawing and outer appearance of the feeler are given in fig.6 and 7. The sensitive and mechanical systems were placed in a strong glass balloon, which can withstand impact overloads of up to 20 g. For convenience during operation the feeler is fitted on a standard base, which allows without difficulty in case of necessity to replace one feeler with another. The working position of the feeler - vertical, the plane of oscillations should be perpendicular to the plane, in which the brackets are situated, i.e. the oscillations should be perpendicular to the long side of the screen of the sensitive system (see fig.6).

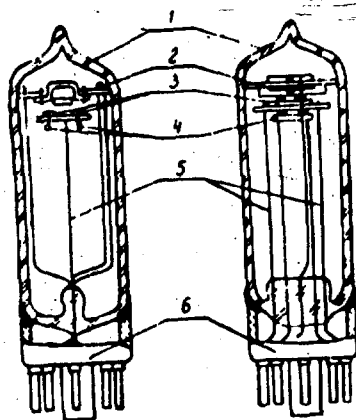


Fig. 6. Construction of Vibrometer (1-feeler balloon; 2-cathode; 3-anodes; 4-inertia load; 5-elastic suspension; 6-base)



Fig. 7. Outer appearance of vibrometer

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As is shown by experiment, the working section of the spectrum of frequency characteristic when functioning in condition of amplitude meter lies in the interval

$$\begin{aligned} 4,3 f_0 \cdot f_{\text{pad}}^{\text{work}} \cdot (1 - 0,03) f_{01} & \quad (6a) \\ (1 - 0,03) f_{01} \cdot f_{\text{pad}}^{\text{work}} \cdot (1 - 0,04) f_{02} & \quad \text{etc.} \end{aligned}$$

Here f_{02} - frequency of second overtone, remaining designations as before.

In addition to the overtone the tube also has an undertone

$$f_{01} \approx \frac{1}{2} f_0. \quad (6b)$$

In the given type of amplitude meter $\frac{f_{01}}{f_0} \approx 12$.

Measuring Circuit

To measure amplitudes and frequencies of vibrations the feeler is connected into a bridge circuit (fig.8). The circuit is balanced, i.e. by changing the resistance values

R_1 and R_2 are attained current lacks in the diagonal. The bridge circuit allows to attain high measurement accuracy, because after its balancing in the diagonal of the circuit is measured only the current differential, and the constant plate current component is absent.

The sensitivity of the bridge circuit with respect to current is determined as a value, numerically equal to the change in current in the bridge diagonal during displacement of the movable feeler electrode by one unit of length. We will designate the sensitivity of the bridge circuit with connected feeler by the symbol S_I , then

$$S_I = \left(\frac{\Delta I}{\Delta l} \right)_{I_a = \text{const}} \quad (7) \dots \text{page 915}$$

Here... Δl - magnitude of displacement of movable feeler electrode relative to the position of equilibrium; ΔI - change in current in bridge diagonal, into the circuit of which the feeler is connected.

We will find expression S_I through the parameters of the bridge circuit, for which the derived expression (2) will be transformed into form convenient for analysis:

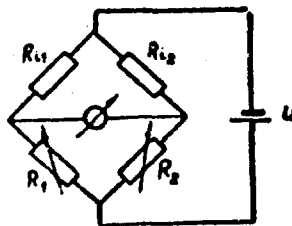


Fig.8. Feeler connection arrangement

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$$S_I = \left(\frac{\Delta I}{\Delta R_i} \right)_{I_a = \text{const}} \cdot \left(\frac{\Delta R_i}{\Delta I} \right)_{I_a = \text{const}} \quad (8)$$

where ΔR_i - change in internal resistance of symmetrical feeler, which brings about the appearance of unbalance current ΔI . Here and henceforth we will assume for simplicity, that we deal with a symmetrical twin end diode, in which the internal static resistances equal R_i . Considerations for nonsymmetrical diodes lead to the very same quantitative dependences, but do require thereat the fulfillment of certain conditions, proof of which goes beyond the scope of this report.

FIRST LINE OF TITLE

Before anything we will show, that in a symmetrical feeler between the relative displacement of electrodes Δl and the change in internal resistance ΔR_i exists a linear dependence, i.e.:

$$\left(\frac{\Delta R_i}{\Delta I} \right)_{I_a = \text{const}} = \text{const.} \quad (9a)$$

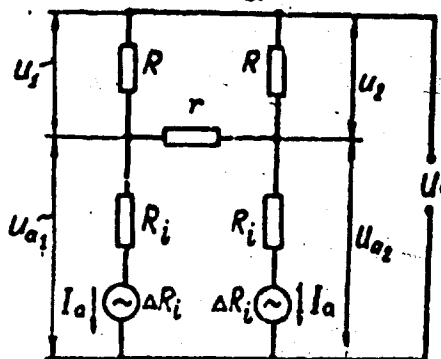


Fig. 9. Equivalent circuit of connecting feeler

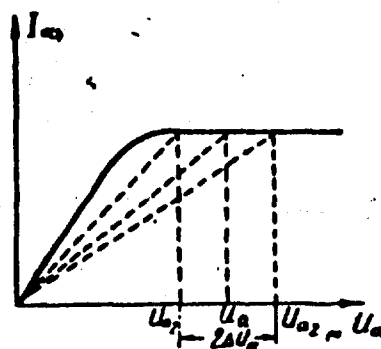


Fig. 10. Voltampere characteristic of diode.

In fig. 9 and 10 is shown the equivalent circuit of connecting the feeler into the circuit of the bridge and the voltampere characteristic of the end diode (twin end diode symmetrical, that is why the characteristics of the diodes coincide). The working point of the end diode is selected on the saturation section of the voltampere characteristic. The change in plate voltage (and consequently of the internal resistance) in the specific range of values ΔU_a (or ΔR_i) does not lead to noticeable change in plate current.

We will assume, that as result of displacement of the movable electrode with

respect to the stationary the internal resistance of diodes has changed by the value

ΔR_1 . We have then a change in plate voltage by the value ΔU_a , but the current, travelling through each one of the diodes, remains unchanged. As result on the left anode of the feeler will be a voltage U_{a1} , and on the right one - U_{a2} at equal currents, travelling through each one of the diodes.

Assuming for the sake of specificity that $U_{a1} < U_{a2}$, then

$$U_{a1} = I_s \cdot (R_1 - \Delta R_1), \quad U_{a2} = I_s \cdot (R_1 + \Delta R_1). \quad (8a)$$

$$U_1 = (I_s + \Delta I) \cdot R, \quad U_2 = (I_s - \Delta I) \cdot R.$$

FIRST LINE OF TITLE

But since

$$U_1 + U_{a1} = U_2 + U_{a2}, \quad (8b)$$

then

$$\frac{\Delta I}{\Delta R_1} = \frac{I_s}{R} = \text{const.} \quad (8c)$$

It is shown in report [1], that in a certain range of values ΔI for such type of feelers exists a dependence

$$\frac{\Delta I}{\Delta I} = 2\alpha_1, \quad (8d)$$

where α_1 - sensitivity of end diode with respect to current.

Consequently

$$\frac{\Delta R_1}{\Delta I} = 2\alpha_1 \frac{R}{I_s} = \text{const.} \quad (8e)$$

Then

$$S_1 = 2\alpha_1 \frac{R}{I_s} \left(\frac{\Delta I}{\Delta R_1} \right)_{I_s = \text{const.}} \quad (9)$$

It can be shown, that the differential current, travelling through the diagonal of unbalanced bridge

$$\Delta I = \frac{\Delta R_1}{RR_1 + [R_1^2 - (\Delta R_1)^2]} \cdot U. \quad (9a)$$

Ordinarily in the feeler

$$R_1^2 \gg (\Delta R_1)^2, \quad (9b)$$

therefore

$$\frac{\Delta I}{\Delta R_1} = \frac{U}{R_1(R + R_1)} \quad (9c)$$

Substituting the obtained expression in (9), we will obtain

FIRST LINE OF TEXT

$$S_1 = 2 \cdot \frac{R}{R_1} = 2 \cdot \frac{U - U_a}{U_a} \quad (10)$$

whereby the value U_a is selected so, that the working point is situated on the saturation section, and the value R is determined from formula

$$R = \frac{U - U_a}{I_a} \quad (11)$$

It is evident from (10) that to obtain maximum sensitivity the value R , and consequently, also U should be possibly greater, and U_a - minimum. The selection of optimum working condition will then be reduced to the following. The voltampere characteristic of the diode is determined experimentally and a working point is selected on the saturation section, situated at a distance $(2-3) \Delta U_a$ from the boundary of the saturation section. Then by the values U_a and I_a found in this way from (11) is calculated the value R . After this is set up a circuit (see fig.8) in which in the bridge diagonal is placed either a measuring device, necessary for final balancing the circuit, or a self-recording instrument, e.g. MFO-2, with which the investigated process will be recorded.

Mode of Operation and Parameters of Tubes

The mode of operation of the feeler is selected in such a way, that the working point is situated in the zone of saturation of voltampere characteristic. In this case even a noticeable change in plate voltage leads to no change in plate current and, consequently, to a change in feeler sensitivity. Furthermore, when functioning in saturation condition the plate currents are maximum. This, in turn, leads to maximum current sensitivity.

The mode of operation of feelers is as follows: $U_a = (40-60) \text{ v}$, $U_f = 6.3 \text{ v}$, $R_1 = 1,2^m$ (1.5 - 6.0) kohms.

Service life over 500 hrs. The mechanical strength is characterized by the fact, that the feelers withstand impact overloads of up to 20 g and vibrational overloads up to 130 g. The accuracy of frequency measurements, frequencies close to $f_{\text{work, min}}$ is determined by equation (5) and may reach 1%. With a rise in working frequency there

is an increase in accuracy (see fig.5).

In table 1 are given parameters of certain feelers at various operational conditions of same.

Table 1.

No. of vibro- meter	U_1 μ	U_2 μ	I_{a1} mA	I_{a2} mA	f_0 Hz	f_{a1} Hz	f_{a2} Hz	S_1 $\frac{mV}{mm}$
1	6.3	42	14.8	14.0	50	600	1500	25.3
2	6.3	70	11.7	11.2	42	530	1000	3.6
3	6.3	60	11.4	11.1	50	$\frac{630}{720}$	1250	4.4
4	6.3	80	21.4	22.6	44	$\frac{600}{760}$	920	17.0
5	6.3	60	13.6	14.5	42	$\frac{520}{660}$	1200	11.8
6	6.3	40	11.7	13.3	45	560	940	14.5

Sensitivity S_1 was determined in the following manner. The feeler was placed on a vibro stand, the oscillations amplitude of which was measured with the aid of an optical microscope. Simultaneously on the film, with the aid of MFO-2 was recorded the oscillation process registered by the receiver. By the sensitivity of the loop and by the measured amplitude of vibro stand vibrations, recorded on the film, it was possible to determine the current sensitivity of feelers.

On fig.11 are given typical oscillograms, obtained for tube No.5 and tube No.4 respectively under working conditions, described in table 1. The oscillograms were obtained at vibration amplitude values of 117 microns and 156 microns. Recording was made on the 5-th loop.

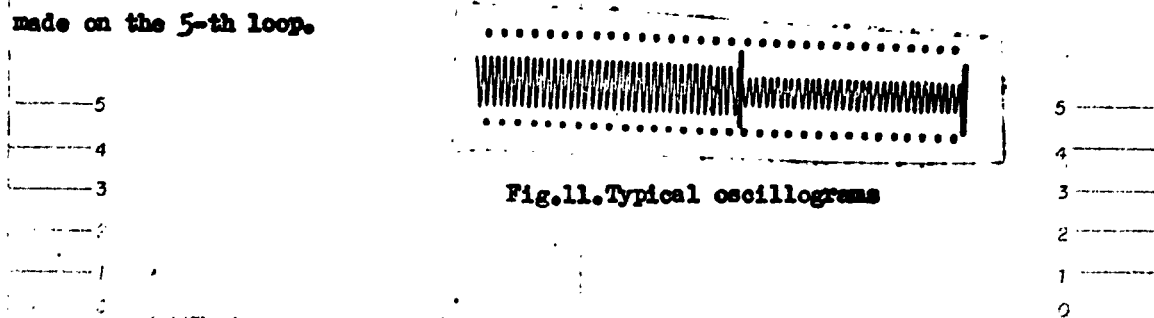


Fig.11. Typical oscillograms

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